

PAMELA/Fermi-LAT electron cosmic ray spectrum at ~ 100 GeV: implication for dark matter annihilation signal in accordance with the 130 GeV γ -ray line

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Abstract

Recently, a tentative 130 GeV γ -ray line signal was identified by quite a few groups. If correct it would constitute a “smoking gun” for dark matter annihilations. Interestingly, the spectra of the cosmic ray electrons detected by PAMELA and Fermi-LAT both show tiny wiggle-like structure at ~ 100 GeV, which might indicate a weak signal of the annihilation of ~ 130 GeV dark matter particles into electrons/positrons with a velocity-weighted cross section $\langle\sigma v\rangle_{\chi\chi\rightarrow e^+e^-} \sim 4 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$. The prospect of identifying such a potential weak dark-matter-annihilation electron and/or positron component by AMS-02, a mission to measure the high energy cosmic ray spectra with unprecedented accuracy, is investigated.

1. Introduction

Gamma-ray line is generally thought to be a smoking gun observation of dark matter (DM). Recently, Bringmann *et al.* [1] and Weniger [2] reported that there might be hint of a monochromatic γ -ray line with energy ~ 130 GeV in the data recorded by Fermi Large Area Telescope (Fermi-LAT) [3]. This γ -ray line could be explained by ~ 130 GeV DM particle annihilation, with the velocity-weighted cross section $\langle\sigma v\rangle_{\chi\chi\rightarrow\gamma\gamma} \sim 10^{-27} \text{ cm}^3 \text{ s}^{-1}$. This phenomenon was confirmed by a series of independent analyses [4, 5, 6]. It was argued that such a line-like structure might originate from astrophysical emission related with the Fermi bubbles

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[7] but the morphology analysis indicated that it is not the case [4]. Based on the identified spectral and spatial variations of rich structures of the diffuse γ -ray emission in the inner Galaxy, Boyarsky *et. al.* argued against the DM origin of these structures [5]. However, the DM origin of the γ -ray line emission has been strengthened by Su & Finkbeiner [6] and by Yang et al. [8]. The independent analyses to search for γ -ray lines in the Milky Way halo by Fermi-LAT collaboration [9] and in dwarf galaxies by [10] found no significant signal, but the constraints are not tight enough to exclude such a γ -ray line signal. It was also proposed that such a line-like signal could be tested with high energy resolution detectors in the near future [11]. Several models had been proposed to explain this tentative line structure [12].

Several years ago ATIC experiment discovered significant excess in the $e^+ + e^-$ energy spectrum between 300 – 800 GeV, moreover the $e^+ + e^-$ energy spectrum also showed possible wiggle-like structure at ~ 100 GeV [13], which has been studied by a few research groups [14]. The e^- spectra measured by PAMELA and Fermi-LAT both revealed tentative fine structure above ~ 100 GeV [15, 16]. Therefore a natural question one would ask is whether there is any connection between the 130 GeV line-like structure of γ -rays and the wiggle structure of electrons.

In this Letter, we focus on the PAMELA/Fermi-LAT electron data and show that the DM scenario with mass ~ 130 GeV corresponding to the possible γ -ray line, might contribute to the tentative fine structure of the e^- spectra around 100 GeV. Together with the PAMELA/Fermi-LAT positron fraction [16, 17] data, we set a constraint on the velocity-averaged cross section $\langle\sigma v\rangle_{\chi\chi\rightarrow e^+e^-} < 10^{-25} \text{ cm}^3 \text{ s}^{-1}$, consistent with all of the current bounds of the indirect detection measurements. Considering the large uncertainties of the current data, more advanced and dedicated experimental observations, in particular by AMS-02², are highly necessary to pin down the shape of the electron and positron spectrum, and then confirm or rule out a DM component in accordance with the ~ 130 GeV γ -ray line.

2. Cosmic ray propagation

The cosmic ray (CR) propagation equation is written as follows [18]:

$$\frac{\partial\psi}{\partial t} = q(\mathbf{r}, p) + \nabla \cdot (D_{xx}\nabla\psi - \mathbf{V}\psi) + \frac{\partial}{\partial p}p^2D_{pp}\frac{\partial}{\partial p}\frac{\psi}{p^2}$$

²<http://www.ams02.org/>

$$- \frac{\partial}{\partial p} \left[\dot{p}\psi - \frac{p}{3}(\nabla \cdot \mathbf{V})\psi \right] - \frac{\psi}{\tau_f} - \frac{\psi}{\tau_r}, \quad (1)$$

where $\psi = \psi(\mathbf{r}, p, t)$ is the density per unit of total particle momentum, $q(\mathbf{r}, p)$ is the source distribution function, D_{xx} is the spatial diffusion coefficient, $\mathbf{V} = dV/dz \times \mathbf{z}$ is the convection velocity, D_{pp} is the diffusion coefficient in momentum space, $\dot{p} = dp/dt$ is the momentum loss rate, τ_f and τ_r are the time scales of fragmentation and radioactive decay.

In general it is difficult to solve the propagation equation with analytical method, given the complicated distributions of the source, interstellar matter, radiation field and magnetic field. Numerical methods are developed to solve the propagation equations, such as GALPROP [18] and DRAGON [19]. In this work we adopt the GALPROP package to calculate the propagation of the CR particles, including the contribution from DM annihilation. The diffusion-reacceleration (DR) and diffusion-convection (DC) models of CR propagation are adopted as illustration. The main parameters of propagation and source injection are compiled in Table. 1. These set of propagation parameters can fit the observational B/C, $^{10}\text{Be}/^9\text{Be}$ and proton data [20].

Table 1: The propagation parameters.

	z_h (kpc)	D_0 ($10^{28} \text{ cm}^2 \text{ s}^{-1}$)	diffusion index ¹ δ_1/δ_2	v_A (km s^{-1})	dV_c/dz ($\text{km s}^{-1} \text{ kpc}^{-1}$)	e^- injection ² γ_1/γ_2	E_{br} (GeV)
DR	3.9	6.6	0.30/0.30	39.2	0	1.61/2.70	4.3
DC	3.9	2.5	0/0.55	0	6	1.63/2.74	4.0

¹Below/above rigidity $\rho_0 = 4 \text{ GV}$.

²Below/above E_{br} .

3. Model and Results

3.1. The contribution of Dark matter annihilation and Pulsars

From the PAMELA and Fermi-LAT data of the electrons [15, 16], we can see that there may be a tiny excess above $\sim 100 \text{ GeV}$. The ATIC and Fermi-LAT spectra of the total electrons and positrons suggest that there is a significant excess at energies above 300 GeV . Therefore we adopt a three-component electron model to fit the data. The background electrons from primary cosmic ray sources contribute to the electrons below $\sim 50 \text{ GeV}$, the pulsar component to reproduce the high energy excesses of the e^+e^- spectra since pulsars are a kind of feasible high

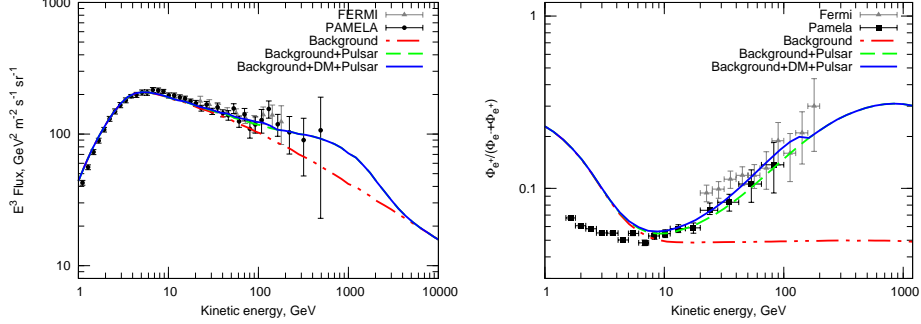


Figure 1: The e^- flux (left) and positron fraction (right) for DR propagation model. The dash-dotted (red) line is the CR background component, the dashed (green) line represents the sum of background and pulsar components, and the solid (blue) line is the sum of the above two and an additional DM component with mass ~ 130 GeV. The annihilation cross section of the DM is $3.9 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$. As shown in the right panel, due to lower flux of the corresponding “background”, it will be easier to identify a DM-origin positron component than the electron component. References of the data are: PAMELA [15, 17], Fermi-LAT [16].

energy positron and electron source that has been widely discussed in literature (e.g., [21, 22]), and the annihilation of DM particles with mass ~ 130 GeV.

The source function of electrons and positrons from DM annihilation is

$$q(E, r) = \frac{\langle \sigma v \rangle_{\chi\chi \rightarrow e^+e^-}}{2m_\chi^2} \frac{dN}{dE} \times \rho^2(r), \quad (2)$$

where m_χ is the particle mass of DM, $\rho(r)$ is the spatial distribution of energy density, and dN/dE is the electron and positron yield spectrum produced by one pair of DM annihilation. In this work we use the Einasto DM density profile [23]

$$\rho(r) = \rho_* \exp\left(-\frac{2}{\alpha_*} \left[\left(\frac{r}{r_*}\right)^{\alpha_*} - 1\right]\right), \quad (3)$$

where $\alpha_* = 0.17$, $r_* \approx 15.7$ kpc and $\rho_* \approx 0.14 \text{ GeV cm}^{-3}$.

We assume that the high energy electrons/positrons are generated through the cascade of electrons accelerated in the magnetosphere of pulsars [21, 24]. The energy spectrum of e^+e^- injected to the galaxy from pulsars can be parameterized as **a broken power-law** with the cutoff at E_c , $dN/dE \propto A_{\text{psr}} E^{-\alpha} \exp(-E/E_c)$, where E_c ranges from several tens GeV to higher than TeV, according to the models and parameters of the pulsars [21, 25]. And the power-law index α ranges from 1 to 2.2 depending on the gamma-ray and radio observations [24]. In this Letter, we

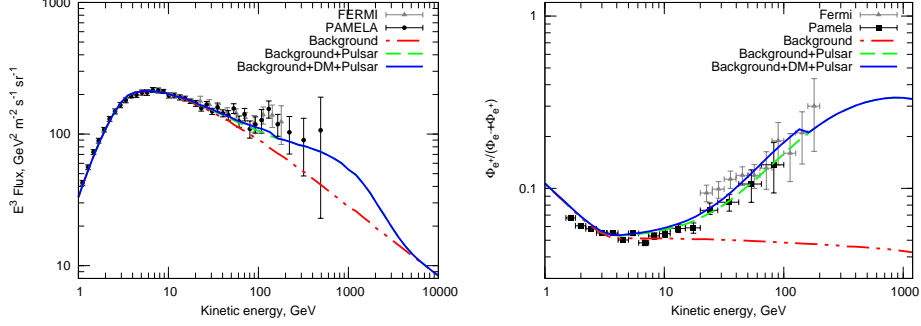


Figure 2: Same as Figure 1 but for the DC propagation model. The DM annihilation cross section is $4.0 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$.

adopt $E_c = 860 \text{ GeV}$ and $\alpha = 1.28$ following [27]. The spatial distribution of pulsars can be parameterized the following form [26]

$$f(R, z) \propto \left(\frac{R}{R_\odot}\right)^a \exp\left[-\frac{b(R - R_\odot)}{R_\odot}\right] \exp\left(-\frac{|z|}{z_s}\right), \quad (4)$$

where $R_\odot = 8.5 \text{ kpc}$ is the distance of solar system from the Galactic center, $z_s \approx 0.2 \text{ kpc}$ is the scale height of the pulsar distribution, $a = 2.35$ and $b = 5.56$. The other parameter appear in the above equation is the normalization factor A_{psr} , and it will be determined in our modeling.

3.2. The Results

Figure 1 shows the results of the three-component model in the DR propagation model. The CR electron background is calculated using the parameters in Table 1. Note for the background positron (and the secondary electron) flux we multiply a constant factor $c_{e^+} = 1.4$ to better fit the data [27], which may account for the uncertainties of the propagation model, interstellar gas distribution and the inelastic hadronic interaction model. To judge the improvement of the fit through adding the $\sim 130 \text{ GeV}$ DM component, we calculate the χ^2 value of the model. To minimize the effect of solar modulation, we use the data with energies higher than 10 GeV for χ^2 calculation, although we employ a force field approximation [28] to approach the solar modulation with modulation potential $\sim 400 \text{ MV}$. The χ^2 for the background + pulsar model (null hypothesis) is 20.9. With the presence of a $\sim 130 \text{ GeV}$ DM component, the minimum χ^2 found is 18.9, and the best-fit cross section is $\langle\sigma v\rangle_{\chi\chi \rightarrow e^+e^-} = 3.9 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$. The fit is slightly improved but not

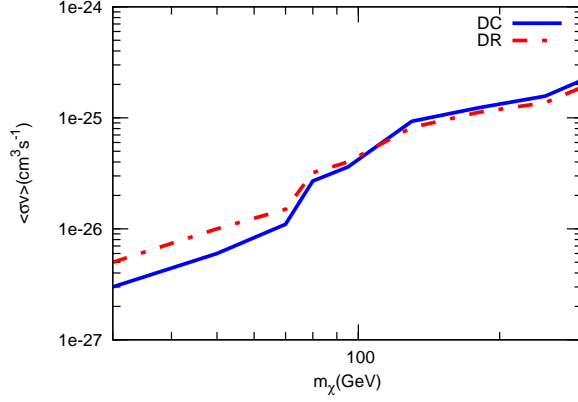


Figure 3: The 2σ upper limits on $\langle\sigma v\rangle_{\chi\chi\rightarrow e^+e^-}$ for DR (dash-dotted) and DC (solid) propagation models respectively.

significantly enough in case of an additional degree of freedom. The small difference between the χ^2 inferred in these two scenarios suggests that the background + pulsar model is enough to describe the data.

Figure 2 is the same as Figure 1 except that it is for the diffusion-convection propagation model. Similarly we calculate the likelihood of the DM component. The χ^2 for the null hypothesis is 21.5, while it is 19.9 in the presence of a 130 GeV DM component. The best fit cross section is $4.0 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$. As in the DR model, the background plus pulsar model gives reasonable fit to the data.

It is shown above that adding a DM component do not significantly improve the fitting, so we turn to set an upper limit of the DM component instead. The 95% confidence level upper limits of the annihilation cross section $\langle\sigma v\rangle_{\chi\chi\rightarrow e^+e^-}$ for different mass m_χ are shown in Figure 3. For $m_\chi = 130 \text{ GeV}$, the 2σ upper limit of the cross section is about $8 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$. This constraint is stronger than that derived through γ -ray observations of the Milky Way halo [9]. One caution is that the constraints also depend on the assumptions used for the background, which are not same as in [9].

Since the current observational data are not precise enough to see whether there is a tiny structure of the electron spectra at $\sim 100 \text{ GeV}$, we would like to discuss the potential of the AMS-02 experiment on this issue. We use Monte Carlo simulation to produce the expected electron spectra of AMS-02, based on the theoretical fluxes of electrons ϕ_e for the background + pulsar + DM scenario as given in Figures 1 and 2. The events number of AMS-02 can be estimated as

[29]

$$N = \Delta t A_e \int_{\Delta E} dE \int dE' \phi_e(E') \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(E'-E)^2}{2\sigma^2}}, \quad (5)$$

where $\sigma = \sqrt{(0.106/\sqrt{E/\text{GeV}})^2 + 0.0125^2} \times E/2$ [30] represent the energy resolution, Δt is the operating time, ϕ_e is the electron flux, and A_e is the geometrical acceptance of electron which is taken to be $0.045 \text{ m}^2 \text{ sr}$ [31]. The electrons are binned into 25 bins logarithmically from 10 GeV to 1 TeV. The observed number of events in each energy bin is generated based on a Poisson distribution with expected value N calculated by Eq. (5). The logarithm of the likelihood function is defined as

$$\ln \mathcal{L} = \sum_i N_i \ln \phi_e^i - \phi_e^i - \ln N_i!, \quad (6)$$

where N_i is the simulated observational electron counts in energy bin i , and ϕ_e^i is the expected counts in the energy bin. The *test statistic* of the DM signal is defined as $\text{TS} = -2 \ln(\mathcal{L}_{\text{null}}/\mathcal{L}_{\text{best}})$, where $\mathcal{L}_{\text{null}}$ is the best fit likelihood of null hypothesis (background + pulsar scenario), and $\mathcal{L}_{\text{best}}$ is the best fit likelihood of the model with 130 GeV DM component. For a series of annihilation cross sections, we calculate the TS value and find the required exposure time T which makes $\text{TS} \approx 25$ (approximately corresponding to 5σ significance). The results are summarized in Table 2. It is shown that if the DM annihilation cross section is larger than $10^{-26} \text{ cm}^3 \text{ s}^{-1}$, this 130 GeV DM signal may be identified by AMS-02.

Table 2: The predicted operating time for AMS-02 to identify the 130 GeV DM annihilating into e^+e^- .

$\langle\sigma v\rangle_{\chi\chi\rightarrow e^+e^-} (10^{-26} \text{ cm}^3 \text{ s}^{-1})$		1.0	2.0	3.0	4.0	5.0
DR	$T(\text{yr})$	7.7	2.2	1.1	0.7	0.5
DC	$T(\text{yr})$	10.0	2.6	1.3	0.8	0.5

We may further note that the DM signal, if exists, will be more prominent in the positron fraction than in the electron spectrum. As shown in Figures 1 and 2, the relative excess of the DM component is only $\sim 2\%$ compared with the background + pulsar flux. However, for the positron fraction the contribution of the DM component could be more than 10% (relative to the background + pulsar components) for the best fit cross section $4 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$.

3.3. Constraints from other observations

The observations of γ -rays (the internal bremsstrahlung and inverse Compton radiation component) and/or radio emission (the synchrotron radiation component) may constrain the current scenario that DM annihilates into electrons/positrons [32, 9]. The lack of evident continual spectrum component associated with the 130 GeV γ -ray line from the Galactic center suggests that the DM particles mainly annihilate into final states with few γ -rays (such as e^+e^- , $\mu^+\mu^-$, or neutrinos), otherwise the observed relic density can not be explained [33]. Such a speculation is one of the main motivation of this work. It was shown that the latest γ -ray observations by Fermi-LAT can constrain the $\langle\sigma v\rangle_{\chi\chi\rightarrow e^+e^-}$ to the level of $10^{-24} \text{ cm}^3 \text{ s}^{-1}$ for DM mass $\sim 100 \text{ GeV}$ [9], which is much larger than the constraint (i.e., $\langle\sigma v\rangle_{\chi\chi\rightarrow e^+e^-} < 10^{-25} \text{ cm}^3 \text{ s}^{-1}$) yielded in this work.

4. Conclusion

The spectra of the CR electrons detected by PAMELA and Fermi-LAT both show small wiggle-like structure at $\sim 100 \text{ GeV}$, potentially consisting of a weak signal of $\sim 130 \text{ GeV}$ DM particles annihilating into electrons/positrons with a cross section $\langle\sigma v\rangle_{\chi\chi\rightarrow e^+e^-} < 10^{-25} \text{ cm}^3 \text{ s}^{-1}$. It maybe connect with the recently reported $\sim 130 \text{ GeV}$ γ -ray line emission which may be the result of DM annihilation in the Milky Way. We investigate the contribution to the electron spectrum and positron fraction of such a DM component. It is found that adding the 130 GeV DM component can improve the fit to the data, but the improvement is not significant enough. We further use the current data to set constraints on the DM annihilation cross section to e^+e^- .

As found in our modeling, the DM-origin electrons/positrons, if there are, are likely less than $\sim 2\%$ (4%) of the background + pulsar e^- ($e^- + e^+$) flux at $\sim 130 \text{ GeV}$. Hence, accurate measurements of the spectrum of the electrons (and positrons) by AMS-02 and DAMPE/CALET³ are highly necessary to test the DM origin of the wiggle-like structure (see Table 2 for the expected performance of AMS-02 in order to identify such a component). Finally we would like to point out that it may be easier to identify a DM-origin positron component than the electron component due to lower flux of the corresponding “background”.

³DAMPE and CALET (<http://calet.phys.lsu.edu/>) are able to measure the total spectrum of cosmic ray electrons and positrons accurately.

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